Response to Referee 1

In the following, the reviewer comment are in blue and our response in black.

The manuscript presents the results of a fully coupled Northern Hemisphere ice sheet—climate model applied to the last two glacial terminations. The manuscript is well-written and nicely illustrated. The description of the model, coupling and sensitivity analysis is mostly clear but could benefit from some minor additions. Overall, I enjoyed reading this paper and I am sympathetic to the aims. I am not suggesting the authors conduct additional experiments. I hope my comments help in improving the manuscript.

Thanks for your your positive evaluation of our manuscript and your useful comments. We have taken them into account for our revised version. Detailed answer to your individual comments are provided in the following.

Comments

Alternative PGM ice sheet geometry:

The manuscript would benefit from a more detailed explanation of how the alternative ice sheet geometry has been applied. In the methods section, it is only briefly mentioned in L169 and in the results (L345 to L348). It would be valuable to explore the regional and large-scale impacts on the climate resulting from this new ice sheet configuration as well as its implications on the timing and on the deglaciation history during the TII.

We agree that we did not put too much weight on these sensitivity experiments in the initial version of our manuscript. The alternative ice sheets have been obtained by changing regionally the ablation parameters during the ice sheet spin-up (uncoupled experiments). These parameters were increased in North America (more melt) and reduced in Eurasia (less melt). Then we simply used these new ice sheets as initial ice sheet conditions for our transient alternative TII experiments. We added a few sentences in the revised manuscript to make it clearer.

We have also included a figure that present the individual ice sheet volume evolution (Fig. RA1) through TII for the three initial ice sheet states. As shown in this figure, there is no major differences between these experiments using alternative geometries and the reference experiment. The largest Eurasian ice sheet helps maintaining a colder Northern Hemisphere climate. This tends to delay the retreat of all the Northern Hemisphere ice sheets, including the North American one. Although initially smaller compared to our reference configuration, the North American ice sheet retreats almost one thousand years later when using the largest Eurasian ice sheet. These additional elements of discussions have been added in the revised manuscript.

The revised manuscript now contains a discussion section in which we present the atmospheric circulation differences between the PGM and the LGM, focusing on the impact of these different ice sheet topographies.

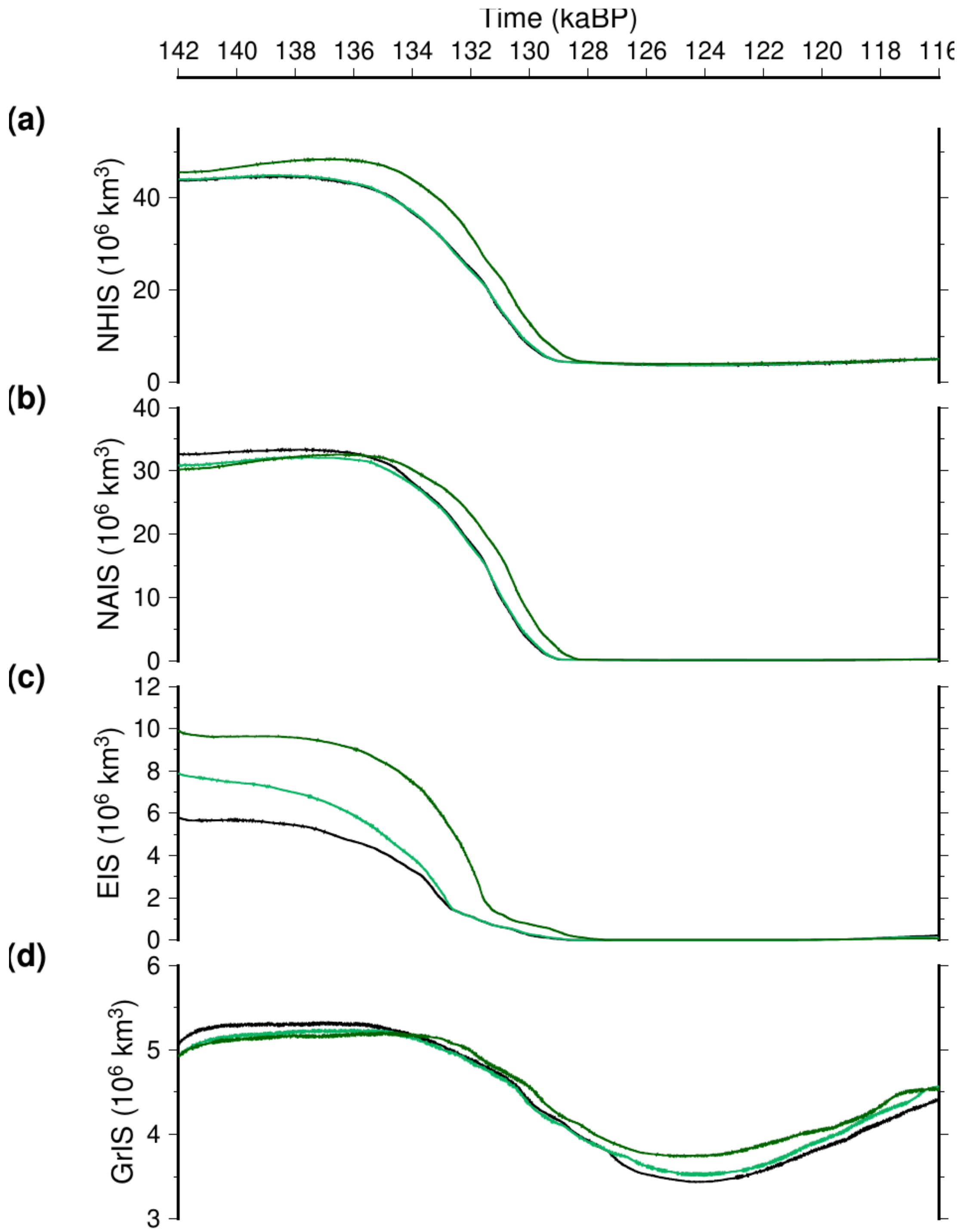

Figure RA1. Temporal evolution of individual ice sheet total ice volume across TII using different initial ice sheet geometries. **(a)**: Total North Hemisphere ice sheet volume. **(b)**: North American ice sheet volume. **(c)**: Eurasian ice sheet volume. **(d)**: Greenland ice sheet volume. The experiment that uses the reference ice sheet is in black while the experiments with slightly larger (+36 %) and larger (+71 %) Eurasian ice sheet volume are in light and dark green, respectively.

Atmospheric resolution:

It would be beneficial to include a discussion on the limitations due to the climate resolution. The simulations are based on the intermediate complexity climate model iLOVECLIM, with an atmospheric resolution of T21. Previous studies have established the implications of coarse-resolution climate models in the modelling during the last glacial maximum and the deglaciation (eg. Lofverstrom et al., 2018; Lohmann et al., 2021).

It is true that the atmosphere in iLOVECLIM is simplified and uses a coarse resolution. The dynamical core uses the quasi-geostrophic approximation with some additional ageostrophic terms for a better representation of the Tropical circulation, in particular Hadley cells (Opsteegh et al., 1998). We agree that the atmospheric model resolution, but also simplification in its physics, can have important impact on atmospheric dynamics and ultimately on the simulated ice sheets. This is now discussed, also with respect to the existing literature, in the new discussion section of the revised manuscript.

Notably, we show that smaller North American ice sheets / larger Eurasian ice sheet produce increased winter precipitation in Eurasia and decrease in North America. This result is somewhat symmetrical to the one of Beghin et al. (2015) who showed that the topographic effect of the North American ice sheet reduces the precipitation in Eurasia through planetary wave changes. It is also consistent with Liakka et al. (2016) that suggested that the development of a large Eurasian ice sheet in its eastern part is favoured by smaller than LGM North American ice sheet.

Other concerns:

To make the paper more accessible to a broader audience, including non-modellers, it may be helpful to explicitly state that the primary aim is not to precisely replicate the timing and pattern of deglaciation but rather to explore the model's sensitivity throughout both terminations. This clarification can aid in ensuring that readers from various backgrounds can appreciate the study's objectives and outcomes.

We have added the following towards the end of the introduction:
“Using a relatively simplified setup, we do not aim to precisely match the available proxy data but instead we aim at better understanding the role of external forcings (orbital configuration and greenhouse gas concentration) on glacial terminations.”

Technical comments:

L231. “In ?”

Sorry for this, it should have been “In Quiquet et al. (2021)”. Corrected.

L245. its written “kyrs” while in some other parts of the text is written “kyr” (eg. L283). Moreover, in other parts is written “ka” (L292). Please check.

Thanks for pointing these inconsistencies. We now use “ka” for durations and “kaBP” for dates.

Figs. 1 - 13. It is written “kaBP” while in Figs 14 and 15 “ka BP”.

We have changed Fig. 14 and 15 to be consistent with the rest of the paper.

Fig 7. Keep the design of the other figures

Changed, we have put all the y-axis on the left-hand side of the figure.

Fig 12. Replace “rhe” for “the”

Corrected.

Fig. 13. Include legend

Done.

Fig 14 and 15. Keep the design of the other figures

In the rest of the paper, the two terminations are shown in the same panel using two different colours. It is true that here we have separated the two terminations in two distinct panels. The reason is that we have to show 5 different experiments (ALL, ORB, GHG, ICE and VEG) for the two terminations. Grouping all this information in one panel would have made the results difficult to read. We have kept our representation with two panels but we have made some small adjustments to make the design of this figure more in line with the rest of the paper (x-axis separated from the y-axis for example).

Lofverstrom, M., & Liakka, J. (2018). The influence of atmospheric grid resolution in a climate model-forced ice sheet simulation. The Cryosphere, 12(4), 1499-1510.

Lohmann, G., Wagner, A., & Prange, M. (2021). Resolution of the atmospheric model matters for the Northern Hemisphere Mid-Holocene climate. Dynamics of Atmospheres and Oceans, 93, 101206.

Reference

Opsteegh, J. D., Haarsma, R. J., Selten, F. M., and Kattenberg, A.: ECBILT: a dynamic alternative to mixed boundary conditions in ocean models, Tellus A, 50, 348–367, https://doi.org/10.1034/j.1600-0870.1998.t01-1-00007.x, 1998.

Response to Referee 2

In the following, the reviewer comment are in blue and our response in black.

Summary:

The study by Quiquet and Roche analyzes various aspects of the climate and ice-sheet evolution in the last two glacial terminations using the intermediate complexity model iLOVECLIM with an interactive ice sheet component. Experiments are presented in which the model is integrated forward from the glacial maximum state (LGM and PGM) through the deglaciation and the interglacial periods. Sensitivity experiments that isolate the influence of individual forcings (e.g., meltwater fluxes, insolation changes, greenhouse gas variations, etc.) are also conducted. The main conclusions are: (i) the Last Interglacial was warmer and had a higher sea-level than the Holocene; (ii) insolation variations is the main driver of glacial retreat during both interglacial periods; (iii) the Atlantic overturning circulation is found to be more sensitive to collapse under Last Interglacial forcing.

The main novelty of the manuscript is the side-by-side comparison of the last two deglaciations in a coupled model setting. However, it is not clear from the presentation what the truly new results are and in what way this study is advancing our understanding of the last two deglaciations. There are several reasons for this, but most importantly because (i) the manuscript does not include a dedicated discussion section where the results are contrasted with the established literature; (ii) the model is quite simplistic and may not be the most appropriate choice for this type of study; (iii) some of the results are undoubtedly model dependent as they contradict previously published results using other models.

I recommend major revisions before this manuscript can be accepted for publication.

Thank you for your thorough review of our manuscript. We have revised the text according to your suggestions. Notably we have added a dedicated discussion section where we discuss simulated atmospheric circulation changes between the LGM and the PGM, using different ice sheet geometries. In this new section, we also discuss our results with respect to the existing literature.

Major comments:

No discussion section:

The lack of a dedicated discussion section makes it hard to get a sense for how the results compare to the established literature and what the potential shortcomings of the study are. You do cite several papers in the results section, but these are primarily used to quantify (and to a certain extent justify) your results. A dedicated discussion section is essential for any study, and this manuscript would certainly benefit from having one as well.

We have added such a section in the revised version of our manuscript. The discussion section focuses on the atmospheric circulation changes, the impact of the initial chosen ice sheet geometry and a broader discussion with respect to existing literature.

QGPV model at low resolution:

I wonder how appropriate the model choice is for this study. From reading the model description in Quiquet et al. (2021), the atmospheric component of iLOVECLIM is a spectral, quasi-geostrophic potential-vorticity (QGPV) model that was run at a nominal 5.6-degrees (T21) horizontal resolution.

It seems to me that this model choice is potentially problematic for at least two reasons:

(i) Several studies have shown conclusive evidence that the numerical convergence of both dry and moist dynamical cores breaks down somewhere between the T31 and T21 resolutions (e.g., Polvani et al. 2004; Lofverstrom and Liakka, 2018), and that resolution can have a substantial influence on the simulated climate (Lohman et al., 2021). The reason for this breakdown is (most likely) that the grid spacing becomes comparable to, or even exceeding the Rossby deformation radius in midlatitudes on sufficiently coarse model grids. This means that baroclinic waves are not appropriately resolved, which are one of the main drivers of the large-scale atmospheric circulation, including the distribution of temperature, precipitation, and wind in mid and high latitudes. While I recognize that it may not be feasible to run the simulations at a different resolution, this potential shortcoming should at least be acknowledged and discussed in the manuscript.

Following your other comment, we have added a discussion section in the revised manuscript, in which we confront our results to existing literature more thoroughly and we present the limitations related to model resolution and physical approximation. We also show the simulated atmospheric circulation differences between the LGM and the PGM.

We show that smaller North American ice sheets / larger Eurasian ice sheet produce increased winter precipitation in Eurasia and decrease in North America. This result is somewhat symmetrical to the one of Beghin et al. (2015) who showed that the topographic effect of the North American ice sheet reduces the precipitation in Eurasia through planetary wave changes. It is also consistent with Liakka et al. (2016) that suggested that the development of a large Eurasian ice sheet in its eastern part is favoured by smaller than LGM North American ice sheet.

(ii) I would like to see a thorough discussion on the appropriateness of using a QGPV model as the atmospheric component in a coupled, global model configuration. QGPV is a decent first-order approximation of the synoptic and planetary scale circulation in mid and high latitudes, but it is not an appropriate description of tropical and subtropical circulation where ageostrophic processes dominate because of the smallness of the Coriolis parameter near the equator. Can we really trust a coupled atmosphere-ocean model that is largely incapable of representing the low-latitude atmospheric circulation with even first order accuracy?

The reviewer raises indeed an important limitation of quasi-geostrophic models. However this problem has been identified during the initial development of the model. ECBilt includes ageostrophic terms in the vorticity equation (Opsteegh et al., 1998) that are neglected in the traditional QG approximation. These terms are computed diagnostically from the wind divergence and the tendency of the streamfunction, using an iterative method. We have added this precision of the revised version of the manuscript.

More generally, even with such limitations, this class of models has been proven useful in the past to study global climate dynamics on millenial timescale. An example of such study on the East-Asian Monsoon system (Caley et al., 2014, Nature Comm.) has shown that the model can reproduce some aspects of the multimillenial precipitation evolution in such regions favourably when compared with water isotopologues proxy records. A few additional examples of studies that have used iLOVECLIM or LOVECLIM model and published in highly-cited journals could further include Roche et al. (2004), Renssen et al. (2015), Menviel et al. (2018), Golledge et al. (2019), Menviel et al. (2020), Yin et al. (2021), Park et al. (2023), and many more. Therefore, it is fair to write that such models have been evaluated and confronted to palaeo-data on a range of diverse applications and that their versatility in computing sensitivity experiments renders them somehow more robust than GCMs that have mostly only run time-slices experiments for dedicated time period.

No discussion about atmospheric circulation changes:

Previous studies have shown that the large-scale atmospheric circulation is strongly influenced by both the height and spatial distribution of the Northern Hemisphere ice sheets (e.g., Lofverstrom and Lora, 2017; Kageyama et al. 2021). Importantly, it has been shown that the North American ice sheet affects the temperature and precipitation distribution (i.e., the surface mass balance) over the Eurasian Ice Sheet (e.g, Liakka et al., 2016).

I think this study would be more convincing if the authors also included figures showing changes in the atmospheric circulation. Not least since the ice-sheet mass balance (i.e., the deglaciation) is to first order driven by changes in the temperature and precipitation distribution, and the QGPV atmospheric model is quite simplistic and may not capture some of the main circulation changes identified in numerous other studies using more comprehensive models.

Atmospheric circulation difference between the LGM and PGM is now shown and discussed with respect to the existing literature. Our precipitation changes resulting from ice sheet changes are somewhat consistent with the results of Beghin et al. (2015) or Liakka et al. (2016).

With respect to the quality of SMB with more comprehensive models, it has been shown on several occasions GCM model outputs are not necessarily appropriate to drive ice sheet models. Using outputs from PMIP3 and PMIP4 model ensemble, both Niu et al. (2019) and van Aalderen et al. (2023) have shown that only a subset of these models were able to maintain reasonable Northern Hemisphere ice sheets at the LGM. The simulated ice sheets at the LGM with iLOVECLIM are not too far from the reconstructions which is an indication that the model is not drastically misrepresenting the LGM climate.

Model dependence:

It is compulsory to discuss potential model dependence on results and conclusions in any modeling study. You mention model dependence in a few places in the text, but it would be good to consolidate this in a dedicated discussion section. One of your main conclusions is that insolation is more important for deglaciation than vegetation changes. I agree that this is what your results shows, but it appears to be contradicting the results in, e.g., Sommers et al (2021), who argued that vegetation changes are at least equally important, if not more important than insolation changes for the deglaciation of Greenland in the Last Interglacial. This is just one example of potential model dependence of your results that should be acknowledged and properly discussed in the manuscript.

We agree that we only use one climate model and that our results are representative of this specific model. We do think that inter-model comparison exercises are really useful with this respect so that we can compare model-specific behaviour to more general responses to forcing changes. This is why we have participated to PMIP4 LGM (Kageyama et al., 2021) and deglaciation experiments (in preparation) with our version of the iLOVECLIM model. We follow the same strategy with the GRISLI ice sheet model, participating to the recent ISMIP6, ABUMIP and LarMIP experiments. Outcome of such participations is that our models are not particularly standing out with respect to other participating models.

Unfortunately, there is not yet any intercomparison exercise of coupled ice sheet – climate model simulations of glacial terminations. One reason is that it is far out of reach from most GCM modelling groups at present, but this might change in the future thanks to better computational facilities and improved numerical scaling.

The paper of Sommers et al. (2021) is indeed very relevant since they used a coupled ice sheet – climate model to simulate the last interglacial period. However a direct comparison of this study with our work is not obvious. While we simulate the entire glacial termination, starting from the PGM, Sommers et al. (2021) start their simulation close to the peak insolation of the LIG, at 127 kaBP. Thus they focus on Greenland ice sheet change, not Northern Hemisphere ice sheets. That being said, if our results show that the vegetation change is not the major driver for Northern Hemisphere ice sheet retreat during TII, we nonetheless simulate a larger Greenland ice sheet volume during the LIG when vegetation change is discarded (+20% in ice volume). This is consistent with the work of Sommers et al. (2021). We have added the comparison with this work in the new discussion section of our revised manuscript.

General experiment design:

I am confused by the experiment design. The introduction states that the Northern Hemisphere ice sheet distribution in the PGM and the LGM were quite different, where the former had comparatively more ice in Eurasia relative to the LGM, and vice versa in North America.
However, the experiments presented here use the same ice sheets as initial conditions for both the LGM and the PGM. What is the reason for this choice since this appears to be a substantial deviation from reality? Would a different ice sheet initial condition alter the results in any way, for example through differences in the large-scale atmospheric circulation?
I recognize that spinning up the ice sheets for the PGM is a major task that may be computationally unfeasible. Therefore, I am not necessarily recommending that you re-run the simulations with more appropriate ice sheets for the PGM, but a discussion of the potential influence of these types of deviations from reality should at least be recognized and appropriately discussed in a dedicated discussion section.

Sensitivity experiments with different ice sheets at the LGM (smaller North American ice sheet and larger Eurasian ice sheet) were already part of the initial manuscript. However, it is true that we did not expand too much on the outcomes of these experiments. We have now added more description of the results of these sensitivity experiments. We also discuss the impact of different topographies on the simulated atmospheric circulation.

The motivation for having identical ice sheets as initial conditions for our transient experiments is twofold:
- The extent and size of the PGM ice sheets is a scientific question in itself. There are currently large field-data uncertainties which make these ice sheets a relatively weak target from a modelling point of view.
- Starting from the same ice sheets is a way to more directly quantify the impact of the different external forcings on climate and ice sheets during the last two terminations.

To make it clearer that our model experiments are a simplification of actual past changes we have also added this in the introduction section:
"Using a relatively simplified setup, we do not aim to precisely match the available proxy data but instead we aim at better understanding the role of external forcings (orbital configuration and greenhouse gas concentration) on glacial terminations."
We also come back to this assumption in the discussion section.

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